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TECHNICAL REPORT ARLCB TR-85026

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TERRAIN SCENE ANALYSIS AND OBSTACLE RECONSTRUCTION FOR NAVIGATION OF MOBILE ROBOTS

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AUGUST 1985

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: ARLCB-TR-85026	2. GOVT ACCESSION NO.: AD-A159469
3. RECIPIENT'S CATALOG NUMBER:	
4. TITLE (and Subtitle): TERRAIN SCENE ANALYSIS AND OBSTACLE RECONSTRUCTION FOR NAVIGATION OF MOBILE ROBOTS	5. TYPE OF REPORT & PERIOD COVERED: Final
	6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): C. N. Shen (See Reverse)	8. CONTRACT OR GRANT NUMBER(s):
9. PERFORMING ORGANIZATION NAME AND ADDRESS: US Army Armament Research & Development Center, Benet Weapons Laboratory, SMCAR-LCB-TL, Watervliet, NY 12189-5000	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: AMCMS NO. 6111.01.91A1A, PRON NO. 1A425M51A1A
11. CONTROLLING OFFICE NAME AND ADDRESS: US Army Armament Research & Development Center, Large Caliber Weapon Systems Laboratory, Dover, NJ 07801-5001	12. REPORT DATE:
	13. NUMBER OF PAGES:
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Presented at the Conference on Intelligent Systems and Machines, Oakland University, Rochester, MI, 24-25 April, 1984.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Terrain Scene Analysis
Object Reconstruction
Robot Navigation
Surface Slopes
Three-Dimensional Space Curves

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

For a robot to be able to perform a task in a dynamic workscene, it must be able to identify the objects in the scene. To achieve this objective, a form of sight must be provided. The first stage in achieving sight is the collection of visual input data. This input is in the form of depth information, such as that received from a laser range finder.

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Unclassified

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20. ABSTRACT (CONT'D)

The laser range finder for a mobile robot is mounted on a mast from which a noisy measurement matrix is generated. This range matrix has a grid with azimuth angles as its abscissa and elevation angles as its ordinates. With these noisy measurements, a rapid estimation scheme is used to detect the presence of horizontal and vertical edges on a terrain by processing the range data successively along each column and row of the range matrix. Many points in a three-dimensional space are generated by estimating sudden change in the range and range slopes using detection scheme with a decision tree. The result of the estimation is a collection of data points to form a curve in space that belongs to some edge of an obstacle from the vantage point where the laser range finder is located. The orthogonal surface slopes of an obstacle can be determined from the range slopes which are estimated from the range matrix. The segmentation of range data on the basis of surface slopes provides groups of connected data points that belong to one particular face of some observed obstacles. The problem of grouping range data points of different planar surfaces on the basis of their surface slopes becomes an application of clustering analysis.

A data clustering and surface fitting operation must be performed and the location of edges and vertices must be determined. Objects are then assembled from these surfaces, edges, and vertices. There are no a priori knowledge of the number of objects in the workscene, however, it is assumed that all the objects in the scene can be approximated modeled as having many planar surfaces. Limitations of a sight system depend on the form of input data used. Systems such as laser range finder systems, which use range information directly, cannot determine edges between objects which are in close alignment. Clearly none of these input data styles can determine the scene description perfectly; therefore, any object recognition scheme would strive for consistency.

The first approach of a heuristic scheme for object reconstruction and formation is presented here based on input data containing depth information. This scheme will reconstruct plane faceted objects from a workscene described as edges, faces, and vertices in cartesian coordinates. The set of heuristic rules is based on geometric considerations and insight into the characteristics of objects, which are found to be the convexity and colinearity of edges. Methods for determining if an edge is convex or concave and if two edges are colinear are developed. These methods are consistent, regardless of the viewer's point of observation. If parts of the image of the workscene in the input information exhibit certain properties, then these parts will be grouped as an object.

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INTRODUCTION

There are many drawbacks of using two-dimensional images for a three-dimensional description of the scenes, the notable ones being: the absence of depth information, and strong vulnerability to disturbing influences of ambient lighting which may cause serious errors in the final interpretation of the images (refs 1,2). To afford a three-dimensional interpretation of a scene from its plane image, the idea of using multiple images from different vantage points has been utilized. The stereo T.V. technique (ref 3), thus tries to obtain depth measurements of the scene directly by computation from a knowledge of the camera viewing geometries. To enable this, a correspondence must be first established between the images of a point obtained by different sensors. Much computational complexity is associated with this correspondence problem and even then the solution is not guaranteed. In recent years, some attempts have been made to base scene analysis on depth information measured directly from the three-dimensional scene. Thus, this principle has been utilized by Duda and coworkers (refs 1,2), to extract important features like planar surfaces, edges of solid bodies, etc., from the range information measured with a laser range finder. However, the particular feature extraction procedures used in that work, although being simple, have

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[1] D. Nitzan, A. E. Brain, and R. O. Duda, "The Measurement and Use of Registered Reflectance and Range Data in Scene Analysis," Proc. IEEE, Vol. 65, No. 2, 1975.

[2] R. O. Duda, D. Nitzan, and P. Barrett, "Use of Range and Reflectance to Find Planar Surface Regions," IEEE Trans. Pattern Analysis & Machine Intelligence, Vol. PAMI-1, No. 3, July 1979.

[3] Y. Yakimovsky and R. Cunningham, "A System for Extracting Three-Dimensional Measurements From a Stereo Pair of T.V. Cameras," Computer Graphics and Image Processing, 7, 1978.

some limitations. Mainly, the assumptions of having surfaces largely horizontal or vertical, orthogonal faceted bodies, and very little curved surfaces may not be very practical in the usual scenes. Moreover, the thresholding technique used for detecting edges of objects might fail to obtain satisfactory results when the actual changes are less than the threshold value. The system described in this report, in principle, uses a time of flight range finder to obtain range measurements of the workscene by scanning in the elevation and azimuthal directions. The feature extraction and scene description procedures have been studied from a point of view of their utilization for navigation of mobile robots.

Previous work on scene analysis has created a common body of knowledge which will be used in this report. Huffman (ref 4) created a system of labels to represent different types of three-dimensional edges in two-dimensional line drawings. In this coding system, "+" next to an edge indicates a convex edge, "-" indicates a concave edge, and an arrow "→" indicates an outside jump boundary. Shapiro (ref 5) defined a virtual vertex as a vertex formed by an occulsion rather than by the intersection of edges. In Figure 1, vertices A, B, C, D, E, and F are formed by the occlusion. These vertices are therefore classified as virtual vertices. A virtual vertex denotes an edge which is incompletely described (the actual coordinates of an endpoint are unknown). In all of the figures in this report, a real vertex will be denoted by ●,

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[4] D. A. Huffman, "Impossible Objects as Nonsense Sentences," Machine Intelligence, Edinburgh University Press, Vol. 6, 1971, pp. 295-323.

[5] R. Shapira and H. Freeman, "A Cyclic-Property of Bodies With Three-Face Vertices," IEEE Trans. Comp., C-26, 1977, pp. 907-915.

while a virtual vertex will be denoted by o. In a paper on two-dimensional scene analysis (ref 6), Guzman used heuristic rules to decompose a line drawing into objects. These heuristic rules were based on the types of vertices which occur in a line drawing.

THE RANGE FINDING SYSTEM OF SCENE ANALYSIS

A number of important advantages were noted for the scene analysis system using range data over those using intensity information of a plane image. The depth information is directly measured from the scene and is not extracted indirectly from the television or camera pictures, therefore, it is more accurate. The procedure to calculate range from multiple T.V. pictures requires matching of corresponding regions in different pictures and involves lengthy and complex calculations. The exact location and orientation of the various objects in the scene analyzed is calculated with respect to the robot vehicle's frame of reference, which can then plan its sequence of operations. No lighting or illumination is required as the laser range finder provides its own beam to illuminate the scene. Disturbing and interfering effects of ambient lighting such as shadows, reflections, shading, highlights, etc., that seriously impair the reliability of scene analysis procedures based on intensity, have no effect on the range based scene analysis. The complete scheme of the range-finding system of scene analysis may be regarded as consisting of two major sections, the data acquisition and feature extraction section and the object recognition/position and orientation determination

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[6] A. Guzman, "Decomposition of a Visual Scene into Three-Dimensional Bodies," AFIPS Proc. Fall Joint Computer Conference, Vol. 33, 1968, pp. 291-304.

section. The scene analysis system is itemized as follows.

A. The data acquisition and feature extraction section.

1. Scanning scheme.
2. Rapid estimation scheme.
3. Gradient estimation scheme.
4. Segmentation of range data on the basis of surface slopes.
5. Plane/surface fitting and smoothing algorithms.
6. Calculation of continuous inner edges as the intersection of surfaces.
7. Verification of calculated edges with those obtained from rapid estimation scheme.

B. The object recognition/position and orientation section.

1. Grouping of edges and surfaces belonging to individual objects.
2. Estimation of the laser range finder's vantage point for an object.
3. Generation of modeled objects view from the estimated vantage point.
4. Matching of the generated view with the measured one for edges and vertices.
5. More accurate matching by slight variations of calculated vantage point.
6. Recognition of object and determination of its position and orientation.

DATA ACQUISITION AND FEATURE EXTRACTION

The laser range finder of the robotic system is mounted on a mast which separates it sufficiently from the main body of the mobile robot, so that its field of view is not obstructed. There are three separate coordinate systems involved in the whole process: the coordinate system of the laser range finder in which the range measurements are performed, the coordinate system of the robot vehicle in which the various control tasks are defined and executed, and finally, the coordinate system of the terrain for the purpose of navigation.

The Scanning Scheme

A spherical coordinate system is defined for the laser range finder in which the range finder itself is assumed to be at the origin of coordinates and its beam can define a cone of revolution, by rotating about the mast axis. The scene of interest is scanned using small increments of polar angle and azimuthal angle. The range data, r, is arranged in a matrix form with rows showing variation of angle θ and columns showing variation of angle β.

Rapid Estimation Scheme for Edge Detection

The rapid estimation scheme (R.E.S.) (ref 7), detected the presence of 3-D curved edges in the workscene by processing the range data successively along each column and row of the range matrix. An edge was detected by a sudden change in the range and/or range slope using detection scheme with a decision tree. The result of R.E.S. is a collection of 3-D range measurement

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[7]C. S. Kim, R. C. Marynowski, and C. N. Shen, "Obstacle Detection Using Stabilizated Rapid Estimation Scheme with Modified Decision Tree," Proc. of JACC, October 1978.

points that belong to some curved edge of an object. These data points are widely spaced, depending on the data density that was imposed on the scanning scheme through the use of particular values of $\Delta\beta$ and $\Delta\theta$.

Slope Estimation Scheme

Range slopes are defined as the incremental changes in range for corresponding incremental changes in the pointing angles, i.e., range inpath slope = $(\partial r/\partial \beta)$ and range crosspath slope = $\partial r/\partial \theta$. The two-dimensional smoothing algorithm (ref 8) provides smoothed estimates of range and range slopes which are used for calculation of actual terrain surface slopes.

Segmentation of Range Data into Plane Surfaces

Ideally, a plane surface of an object has constant slope along any two fixed orthogonal directions throughout its extent. Using this idea, the observed data points of plane surfaces are grouped into various subsets, one for each surface, on the basis of their "surface slopes." These "surface slopes" are defined as the slopes shown by the surface of the object at the data points. The segmentation of range data on the basis of surface slopes provides groups of connected data points that belong to one particular face of some observed object.

A Clustering Procedure for Extraction of Plane Surfaces

The problem of grouping range data points of different planar surfaces on the basis of their surface slopes becomes an application of clustering

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[8] C. S. Kim and C. N. Shen, "A Two-Dimensional Recursive Smoothing Algorithm Using Polynomial Splines," IEEE Int. Symposium on Info. Theory, 1980.

analysis (ref 9,10), in which:

1. The distinguishing feature vector is $X = [f_1, f_2]^T$, where f_1 and f_2 are the two orthogonal slopes with respect to one of the three coordinate planes of the laser range finder.

2. The number of clusters 'c', in other words, the number of plane surfaces observed in the scene, is not known initially.

3. An initial configuration or rough classification of feature vectors into clusters cannot be obtained by any simple procedure.

4. Feature vectors corresponding to parallel plane surfaces have to be discriminated.

Since an initial partitioning of data could not be found from the given problem specifications, agglomerative hierarchical clustering (ref 9) was used to obtain a reasonable initial partitioning. Moreover, the whole data set is not treated at one time, but a recursive approach is adopted to cover the complete measurement space. Recursive approach was necessary for reducing computation, and differentiating between feature vectors of parallel planes.

To make the classification optimal, the familiar sum of squared errors criterion function (refs 9,10) is minimized. A least squares plane is then fitted to each of the clusters to describe the particular face of some object. The edges of the objects can then be calculated as the intersection of the plane faces.

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[9] R. O. Duda and P. E. Hart, Pattern Classification and Scene Analysis, John Wiley and Sons, New York, 1973.
[10] K. J. Fukunaga, Statistical Methods of Pattern Recognition, Academic Press, 1972.

OBJECT RECONSTRUCTION AND RECOGNITION

Various edges and plane surfaces extracted above are then assembled into meaningful bodies using heuristic rules based on physical constraints of bodies. The strategy adopted for object identification is essentially a model based recognition process. Three-dimensional models of all the objects likely to be present in the workscene are first stored in the computer memory which consist of a specification of the lengths and spatial position of all the edges, the coordinates of all the vertices, and the angles between their component edges. A coordinate system is then fixed in the model and is defined with respect to its vertices and edges observable from outside. The computer memory contains many stored models and an initial guess for the identity of the observed object is based on the lengths of the observed edges and the angles between them, at a particular vertex or face. A similar vertex or face is then searched in the model library and a list of candidate models is drawn. The viewing geometry of the laser range finder is then given by the position and orientation of its axes with respect to the coordinate system fixed in the object.

Assembly Method

A useful clue in the grouping of surfaces into objects is the convexity of edges. Surfaces which intersect at a convex edge are generally part of the same object. This fact alone successfully groups many different objects.

An occlusion will split one object into two half-objects. If possible, these half-objects should be grouped together. The half-edges formed by the occlusion will end in virtual vertices. If two half-edges were part of the same edge, then they would be colinear. Also, the half-faces on both sides of

the occlusion would be coplanar if they were part of the same face.

Using this information, a set of heuristic rules is developed.

Heuristic Rules

Planes will be collected into the same object if they satisfy these rules:

1. Intersect at a convex edge.

2. Contain colinear half-edges which have adjacent coplanar faces.

3. Intersect at a concave edge where one of the vertices of the edge is on the outside edge, and the concave edge is not colinear with the outside edge.

These heuristics are pictorially described in Figure 2, where indicates that the two faces connected are grouped into the same object. Figure 2a shows faces which are grouped because of the convex edge between them. Figure 2b shows faces which are grouped because they contain colinear edges with adjacent coplanar faces. Figure 2c shows an example of grouping according to Rule 3.

Rule 3 is included in the set of rules because a laser range finder, which measures only depth, will not see an edge between objects which are aligned. In Figure 3, Part C will be grouped into the main body when viewed from the right because it contains part of face 1, and face 1 has convex edges which link it to the rest of the main body. Face 1 contains vertices A, B, C, D, E, and F. If this object is viewed from the left, we want the same grouping to occur so that the description of the scene will be consistent. When viewed from the left, Part C can be grouped into the main body by Rule 3. Part A exhibits the same characteristic. Part B is not grouped with the main

body since the concave edge is colinear with the outside edge of the main body.

Using the real world as an example, objects on a table are considered separate objects unless they are aligned with an edge of the table.

Convexity

One of the most important features of the object reconstruction scheme is determining whether or not an edge is convex or concave. We define convexity as follows:

> If the angle between two intersection planes which goes through the object and is perpendicular to the edge of intersection is less than 180 degrees, then the edge of intersection is convex.

To determine if an edge is convex or concave, we define the unit normal vector L_1 and $\hat{L}_2$ for the edge in both planes intersecting at the edge, Figure 4. These unit normal vectors lie in the planes forming the edge, are perpendicular to the edge, and point to the inside of the plane. Then we form the unit vector pointing from the range finder eye to the midpoint of the edge in question and call this vector R. If the dot product of R and the sum of $\hat{L}_1$ and $\hat{L}_2$

$$R \bullet (\hat{L}_1 + \hat{L}_2) \qquad (1)$$

is greater than zero, a convex edge is indicated. If this dot product is less than zero, a concave edge is indicated. Examples of how convexity is determined are shown in Figures 5 through 7, where R_1 is the projection of R into the plane formed by $\hat{L}_1$ and $\hat{L}_2$.

This method of determining convexity is necessary because a simpler

method using the change of sign of the gradient cannot differentiate between the convexity of Figure 6 and the concavity of Figure 7. Only interior edges are checked for concavity. Outside edges are classified as jump boundaries and are noted as being convex.

Colinearity and Coplanarity

All half-edges are searched to see if any pairs are colinear. For two half-edges to be colinear, three of the possible six unit vectors formed by pairs of the four vertices must be equal (Figure 8). We choose to use the pairs (A,B), (A,C), and (A,D), and say if:

$$\frac{AB}{||AB||} = \frac{AC}{||AC||} = \frac{AD}{||AD||} \tag{2}$$

then the half-edges are colinear. If the closest pair of vertices consists of virtual vertices, such as B and C, then the edges are candidates for being merged together into a longer edge. However, the merging is not performed until adjacent coplanar faces are found.

Due to noise in the range data, the edges obtained by the intersection of planes will not be exact. Also, we would like to avoid the necessity of ordering the vertices before checking for colinearity. For this reason, the actual test for colinearity will be:

$$2 - \mathrm{ABS}\,\frac{AB \bullet AC}{||AB||\ ||AC||} - \mathrm{ABS}\,\frac{AB \bullet AD}{||AB||\ ||AD||} < K \tag{3}$$

where K is a small number dependent on the amount of noise.

Half-faces which are coplanar will have equal unit normal vectors associated with the colinear half-edges. However, to take into account the noise in the input data, the actual test for coplanarity of faces will be:

$$||\hat{L}_1 - \hat{L}_2|| < K_2 \tag{4}$$

where K_2 is another constant based on measurement noise.

If Rule 2 is satisfied, then the half-edges are merged and the adjacent coplanar half-faces are merged. In Figure 8, $\hat{L}_1 = \hat{L}_2$, indicating that the half-faces are coplanar. Also, AB is colinear to CD, and both B and C are virtual vertices, satisfying Rule 2. Hence, F2 will be merged with F1 and AB will be combined with CD to form AD.

Results

Computer simulation was performed on an IBM 3033 computer in a program written in LISP. A sample workscene is pictured in Figure 9, where ◎ signifies the position of the laser range finder eye, which is the origin of the cartesian coordinate system in which the input data is recorded.

The input is in the form of lists of features. A face is defined as the list of edges which bound it, an edge is defined as a pair of vertices and contains the information on the unit vectors, and a vertex is defined by this list of its coordinates. For example, face F1 is defined as (EF DF CD CE) in the sample workscene. Also, edge DF is defined as ((F1 0 -1 0)(F2 0 0 1)) where (0 -1 0) is the direction of the unit normal vector associated with F1 at edge DF. Vertex A is defined as (-6 -20 12), its coordinates relative to the range finder eye location. Which vertices are virtual is determined using the fact that virtual vertices are the endpoints of only one edge, while other vertices are formed by the intersection of more than one edge.

The output contains the description of the scene upon completion of the object reconstruction scheme.

The output was:

VIRTUAL VERTICES: (I S T M R Q)

NEWEDGES: (HN BO AP)

CONCAVE: (CD DH)

CONVEX: (DF KV BO)

OBJECT1: (F1 F2 F3 F4)

OBJECT2: (F5 F6)

The scheme actually worked as follows:

- Virtual vertices were found.
- Colinear half-edges were fixed creating NEWEDGES HN BO AP and merging faces F7 and F8 into face F3 and F4, respectively.
- F1 and F2 were linked across convex edge FD.
- F3 and F4 were linked across convex edge BO.
- F5 and F6 were linked across convex edge KV.
- F1 and F2 were both linked with F3 based on Rule 3 at edges CD and DH.

No other links were possible so that the group of faces were then considered objects. Note that F7 and F8 do not appear in any object list since they have been merged away.

CONCLUSIONS

A system for analyzing scenes in navigation application of robot vehicles has been described. The sensor assumed for performing measurements on the workscene is a time of flight range finder. Procedures have been studied for extracting important features of the scene like edges and surfaces of the objects, for describing individual objects by their edges, vertices, and

bounding surfaces, and finally, for recognizing the previously known objects as observed in the scene by comparing the observed features with those of a model stored in the system memory. It is expected that the finally developed system will be able to recognize known objects in their true relative locations with respect to each other and with respect to the robot. The performance of the system will not be affected by variability in position and orientation of objects, and in the illumination conditions of the workscenes.

Heuristic schemes have been proposed in the past for reconstruction of two-dimensional objects. These sets of rules have generally depended on an exhaustive list of the types of vertices that appear in the two-dimensional projection of the workscene. The type of heuristic rules used for two-dimensional object reconstruction are both overly lengthy and not adaptable to three-dimensional object reconstruction.

This report proposes a three-dimensional object reconstruction scheme which uses heuristic rules based solely on three-dimensional geometric considerations. We found that given three-dimensional input describing a workscene, the objects contained in the scene can be reconstructed using these heuristic rules. In cases where enough information is available, parts of the scene which are masked by occlusions can also be rebuilt. The reconstruction is consistent and allows for error due to measurement noise.

The final description of the scene could be utilized in a complete robot sight system, allowing the robot to scan the scene, navigate to some desired position, and perform some task. A robot having such ability would be useful in places where it is undesirable, for environmental reasons, for a human to go and where remote control would be too slow.

In the future, the sight system will be expanded by linking it to an object identification scheme. Objects found in the workscene will be compared with previously stored models in the library. This library will contain information on all objects that could be found in the workscene. Object identification is another step toward providing sight for a robot. Once the objects are identified, control tasks can be planned and executed.

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9. R. O. Duda and P. E. Hart, Pattern Classification and Scene Analysis, John Wiley and Sons, New York, 1973.

10. K. J. Fukunaga, Statistical Methods of Pattern Recognition, Academic Press, 1972.

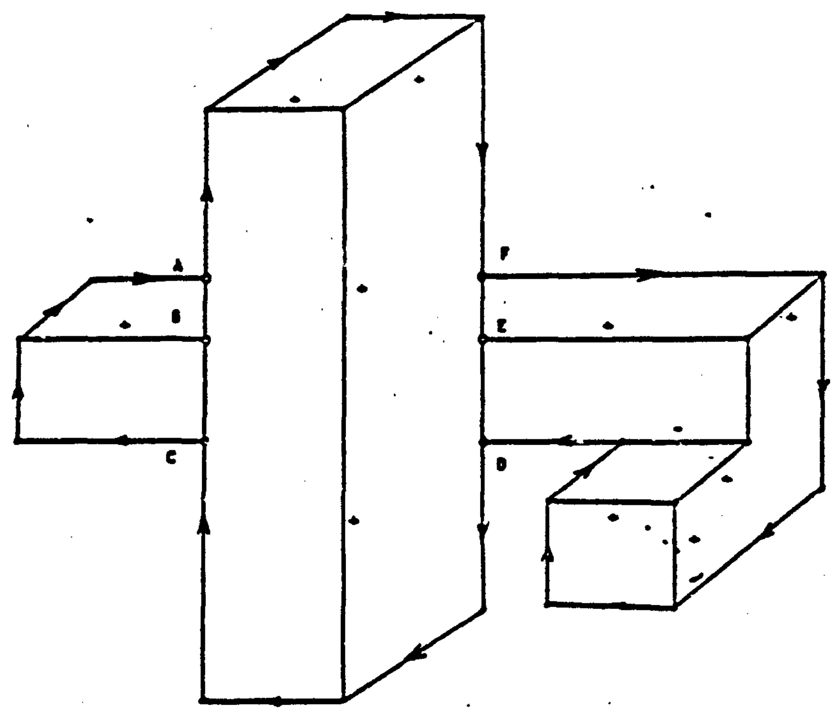


Figure 1. Huffman Coding, Virtual Vertices.

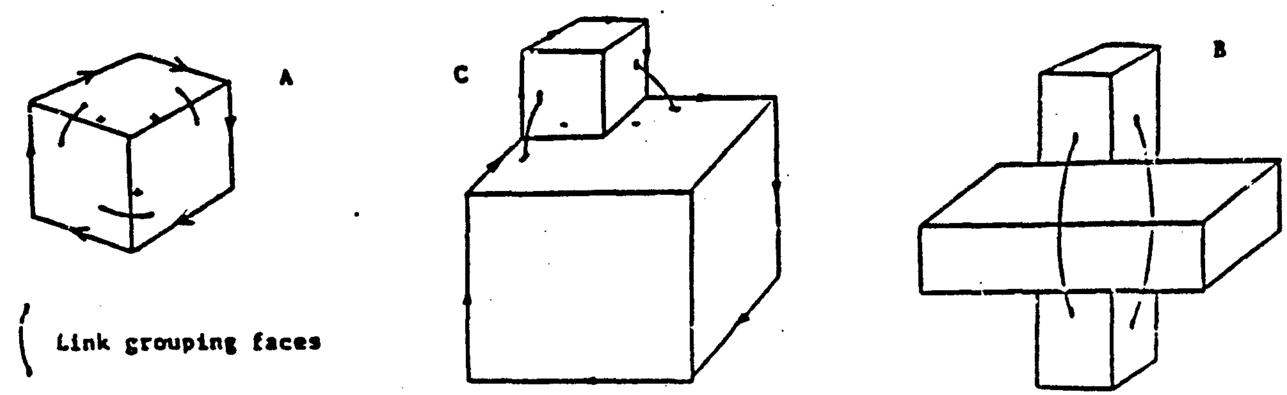


Figure 2. Heuristic Rules.

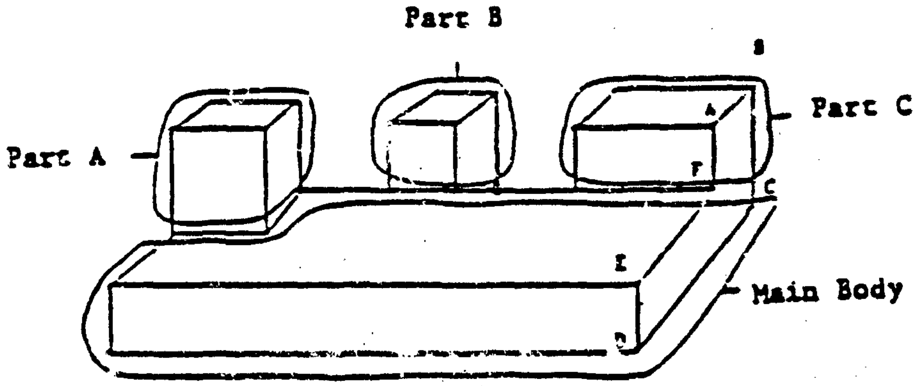


Figure 3. Rule No. 3.

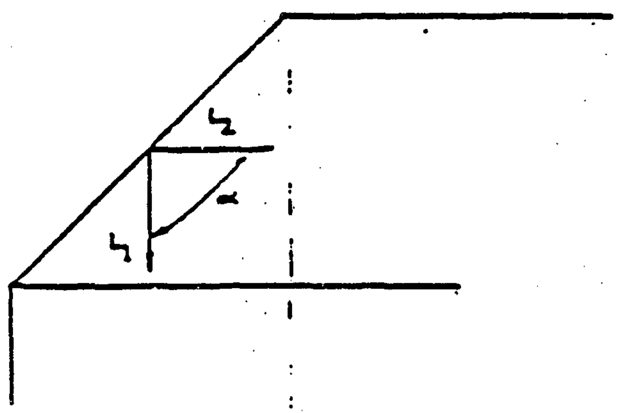
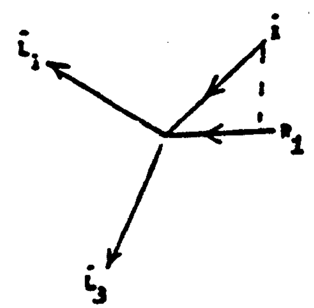


Figure 4. Determining Convexity.



$\hat{L}_1 \cdot \hat{R} > 0 \quad \hat{L}_2 \cdot \hat{R} > 0$

$\hat{L}_1 \cdot \hat{R} + \hat{L}_2 \cdot \hat{R} > 0$

$\therefore$ edge AB is Convex

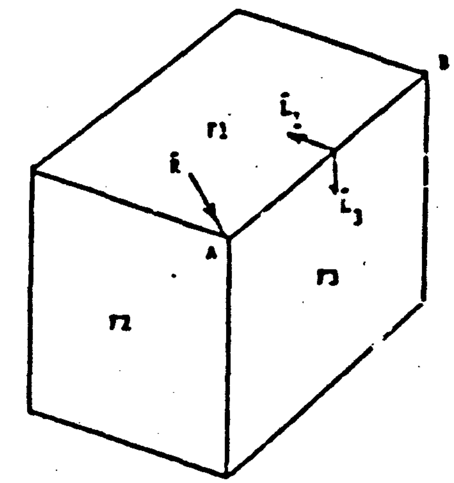
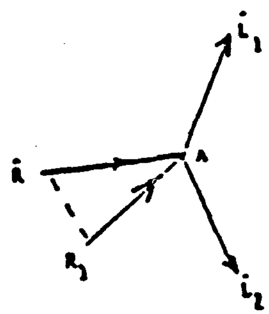


Figure 5. Acute Convexity.



$\hat{L}_1 \cdot \hat{R} > 0 \quad \hat{L}_2 \cdot \hat{R} < 0 \quad |\hat{L}_1 \cdot \hat{R}| > |\hat{L}_2 \cdot \hat{R}|$

$\hat{L}_1 \cdot \hat{R} + \hat{L}_2 \cdot \hat{R} > 0$

$\therefore$ edge AB is convex

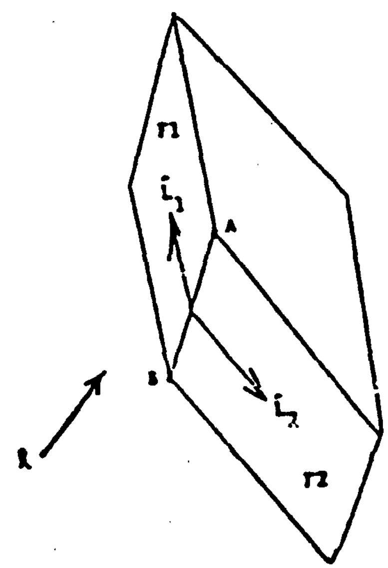
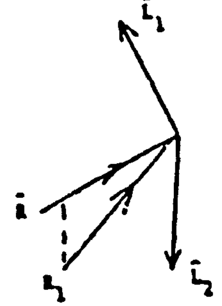


Figure 6. Obtuse Convexity.



$$\hat{L}_1 \bullet \hat{R} > 0 \quad \hat{L}_2 \bullet \hat{R} < 0 \qquad |\hat{L}_2 \bullet \hat{R}| > |\hat{L}_1 \bullet \hat{R}|$$

$$\hat{L}_i \bullet \hat{R} + \hat{L}_2 \bullet \hat{R} < 0$$

$\therefore$ Edge AB is concave

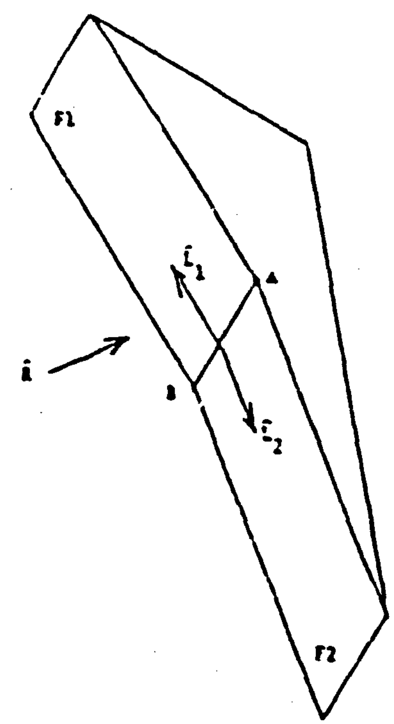


Figure 7. Obtuse Concavity.

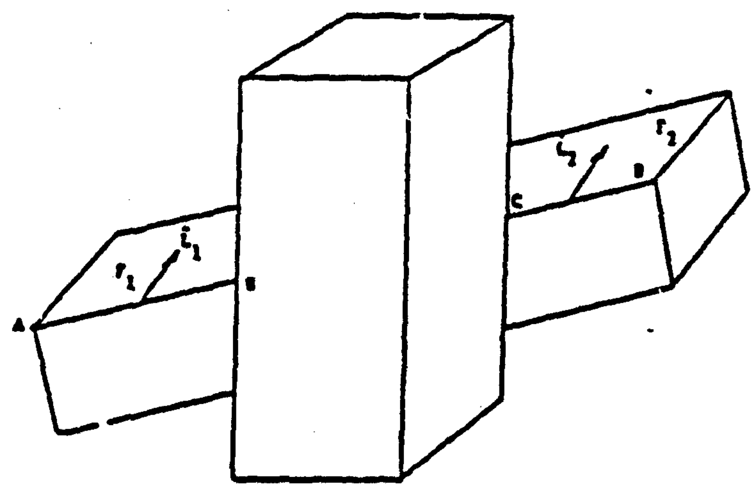


Figure 8. Colinear Edges with Coplanar Adjacent Faces.

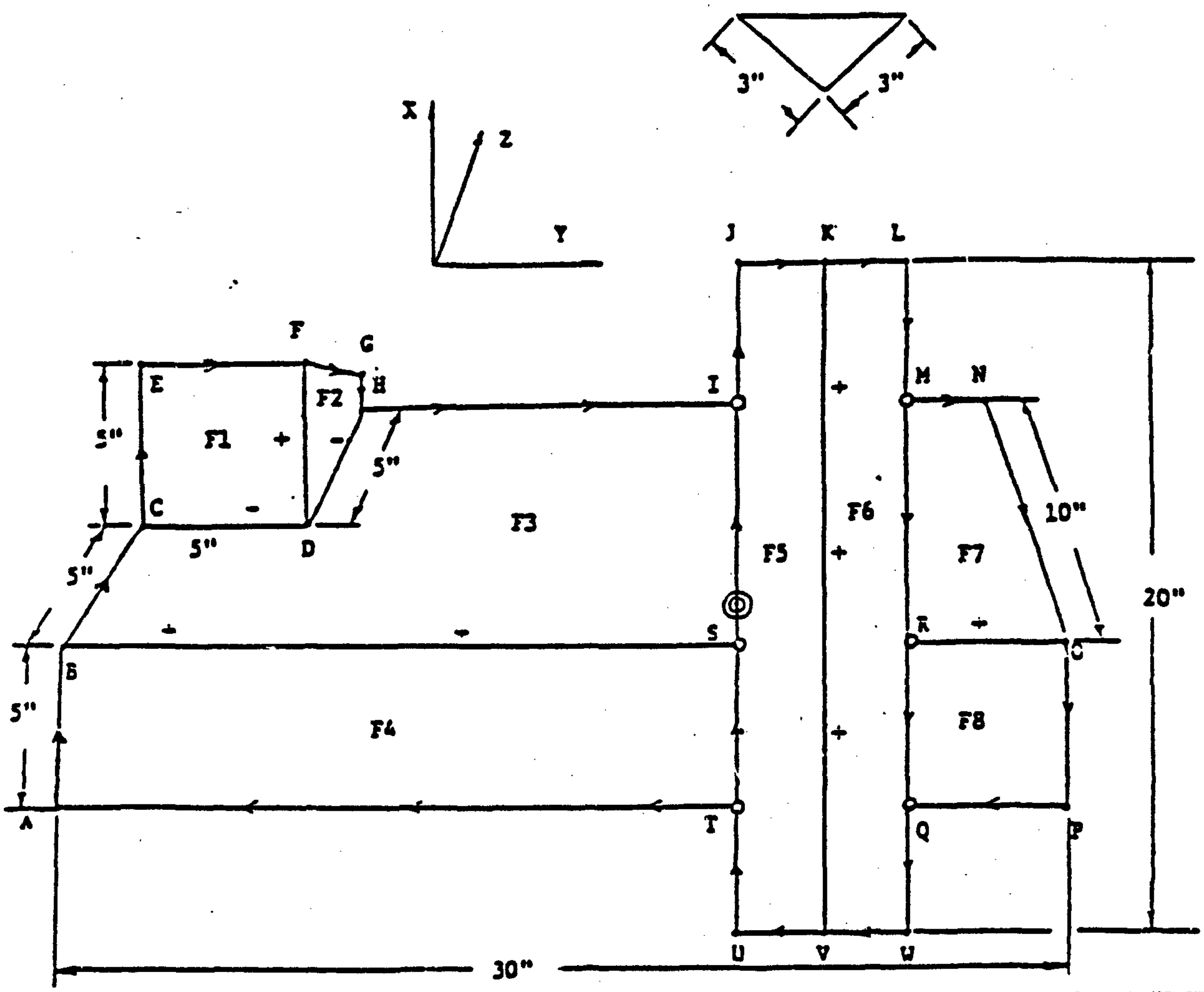


Figure 9. Sample Workscene

● Real Vertice, o Virtual Vertice,

◎ Laser Range Finder Eye Position, One Foot in Frcnt of Workscene

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